UCRL- 93988
PREPRINT

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This paper was prepared for submittal to:
FUSION TECHNOLOGY

January 21, 1986

A RATIONALE FOR NOVEL NEUTRON ENERGY CONVERSION SCHEMES FOR D-T FUSION REACTORS*

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

ABSTRACT

We propose that significant economic advantages can be obtained for DT fusion reactors, relative to competitive technologies, if the expensive and complex conventional steam-turbine power conversion cycle can be replaced with innovative fusion-specific neutron energy conversion schemes. In this way, the inherently higher cost of the fusion nuclear island can be offset by the low cost of the considerably simplified balance-of-plant, and capital costs in the range of conventional fission reactors can be obtained; fuel cost differentials would then enable DT fusion to establish a significant economic advantage relative to fission. We demonstrate that the energy flow from 14 MeV neutrons to heat in an absorbing medium proceeds through four distinct stages via intermediate production of primary and secondary charged particles and that, in principle, we can intercept the energy flow at any stage to generate electricity. We then offer eight possible methods of converting neutron energy to electricity to emphasize that boiling water in a conventional steam-cycle may not necessarily be the only complement to a DT fusion power core. Two of the most promising fusion-specific conversion schemes are selected for futher discussion, namely: in-situ radiation-catalyzed MHD conversion and excimer-channeled UV conversion, and their physical principles are outlined. Finally, in an assessment of the economic implications for both the Tandem Mirror and the Tokamak, we demonstrate that about a 40% or more reduction in the cost of electricity should be possible for DT fusion reactors coupled to such innovative neutron conversion schemes.

1. INTRODUCTION

Currently in the fusion community, there would appear to be a growing sentiment that present concepts for our ultimate reactor product are not sufficiently attractive, at least not in the economic climate of today's energy market. Recent major conceptual design studies of "conventional" fusion reactors such as STARFIRE[1] for the Tokamak and MARS[2] for the Tandem Mirror indicate direct capital costs which are 1.5-2 times greater than equivalent fission plants.* Even when fuel costs are taken into account, the final cost of electricity in mills/kWhr, barely meets that of developed competitive technologies such as light water reactors and fossil-fueled plants. Moreover, recent criticisms by respected researchers and commentators in the fusion field,[3-5] attesting to some undesirable features of our conceptual commercial product (e.g., size, complexity, economics, etc.), have gained increasing public attention.

It is widely accepted that the fusion nuclear island (including magnets, structure, breeding blankets, plasma heating systems, power supplies, etc.) is inherently more expensive than a fission nuclear island. Accordingly, coupling to a complex and expensive conventional steam-cycle "balance-of-plant" can only lead to a more expensive total. For example, in the conceptual designs of the STARFIRE Tokamak Reactor[1] and the MARS Tandem Mirror Reactor,[2] the Reactor Plant Equipment accounted for 56.1% and 64%, respectively, of the total direct cost. If we subtract the cost of the main

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*Cost factors of this order can be obtained from fission database information such as that in Ref. 6 with additional cost-penalty data for fission plants currently under construction.

heat transfer and transport equipment from the reactor plant equipment, then the fusion power core and ancillary systems account for about 50% of the total direct cost in both cases. These figures should be compared with those for projected near-term fission plants,[6] where only ~ 32% of the total direct costs are attributable to the reactor/boiler plant equipment and less than 10% are attributable to the reactor core alone (the initial fuel load is not included in these figures).

Recent innovations in conceptual fusion reactor design have certainly been effective in reducing the relative size of the fusion power core. For example, the MINIMARS tandem mirror reactor[7] employs novel compact end plugs to yield a Tandem Mirror Reactor exhibiting an attractive economy of scale at small (500-600 MWe) sizes with the added advantages of inherent safety. Similarly, in recent designs of the Compact Reversed Field Pinch Reactor,[8] the cost of the fusion island and primary loop has been reduced to ~ 41% of the total direct cost, albeit with relatively large reactor sizes (1000 MWe) and high, possibly detrimental, system power densities (neutron wall loadings are ~ 20 MW/m^2).

Nevertheless, however much we attempt to innovate the fusion nuclear island, it is difficult to see how we will ever approach the simplicity, compactness and economy of a fission reactor core. In addition, it might be argued that for fusion to generate serious widespread interest in today's economic climate, it would have to demonstrate a significant advantage over fission; breaking-even may not be enough! In this paper, we propose that significant economic advantages may be possible if the power conversion systems for DT fusion can be simplified by employment of novel neutron energy conversion schemes. The relatively high cost of the fusion nuclear island can then be offset by low balance-of-plant costs, and total capital costs equal to, or better than, those envisaged by future fission plants could be achieved without sacrificing the environmental or safety advantages of fusion. Fuel cost differentials would then enable fusion to demonstrate a significant economic advantage.

Accordingly, while we are convinced that innovations in the fusion power core will surely continue, we pose the following specific question: Can we exploit the unique characteristics of DT fusion in novel neutron energy conversion schemes, thereby substantially reducing the complexity and expense of the external balance of plant over that of a conventional steam cycle?* Certainly, the decoupling of a 21st Century technology (the DT fusion reactor) from a 19th Century technology (the steam cycle) and recoupling to a lower cost, simpler fusion-specific energy conversion system would greatly enhance the near-term commercial realization of DT fusion.

2. CAN WE DO SOMETHING BETTER WITH 14 MEV NEUTRONS THAN BOIL WATER?

Compared with the other fusion reactions considered for reactor applications, the DT reaction has some significant advantages: it has the largest fusion cross-section (→ highest reaction rate); the peak in the

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*A striking example of the complexity (and, by implication, expense) of the modern steam-cycle balance-of-plant is obtained by reference to the 1290 MWe PWR currently under construction in Brokdorf, Federal Republic of Germany. At the current stage of construction (~ 25% complete), over 2700 kilometers of piping and tubing have been installed[9]!

cross-section occurs at the lowest energy (→ lowest plasma temperature for a given reaction rate); it has one of the highest Q values (→ large energy release per reaction); it contains only singly-charged ($z = 1$) nuclei (→ minimizes plasma Bremsstrahlung radiation losses). For these reasons, it is widely accepted that the DT reaction will provide the basis of the first generation of fusion power reactors. However, the DT reaction releases 80% of its energy in the form of a 14.1 MeV neutron. It could be argued that, even given a successful and workable plasma confinement scheme, it is the inherent properties of this neutron which may, to a large extent, frustrate the near term commercial realization of fusion power, namely: it activates structural material (→ radioactive waste); it has a long shielding mean free path (→ expensive shielding and magnet systems); it will damage first wall and blanket materials (→ limited lifetime and availability); and, perhaps most importantly, we in the fusion community have up to now considered that its energy can only be converted to heat. This last factor implies an expensive and complex steam/turbine balance-of-plant with relatively low associated efficiencies.

We should pause here to emphasize that, on initial emission from the fusion reaction, the neutron can be considered a very low entropy system (remember the effective kinetic temperature of a 14 MeV neutron is ~ 10^{11}K) with its total energy directed in only one degree of freedom. However, if we allow the neutron to slow down in a conventional neutron absorbing blanket, its energy becomes distributed over many degrees of freedom in the bulk heating of the blanket medium. Because of the increased entropy associated with the conversion of neutron energy to heat in the blanket, the efficiency of our conventional fusion blanket and associated steam-turbine cycle is Carnot-limited and dependent on the maximum blanket temperature attainable. Accordingly, we pose the following two questions:

- Is there some way to convert neutron kinetic energy to electric (potential) energy without going through an intermediate heat (and, therefore, Carnot-limited) stage?
- If we have to generate heat, is there some way we can convert the heat energy content to electricity without the use of a conventional steam-turbine cycle with its associated complexity and expense?

Neutrons are uncharged and only interact with matter via nuclear interactions. Accordingly, electrical energy conversion of neutron kinetic energy can only take place after subsequent transfer of this kinetic energy to charged particles. This transfer may also proceed via intermediate gamma ray production. Neutrons finally generate heat in an absorbing medium by successive stages of primary charged particle production and secondary ionization and excitation. In Fig. 1, we illustrate the four stages, I through IV, of energy flow from fusion neutrons to heat. The primary charged particles in stage II arise initially from a number of neutron-nucleus interaction channels: (a) charged particle nuclear reactions, e.g., (n,p), (n,α), etc.; (b) nuclear recoil from elastic and inelastic scattering; and (c) electron production from gamma rays via photoelectric, Compton, or pair-production effects, the gamma rays resulting from neutron capture, (n,γ), or neutron inelastic scattering, $(n,n')\gamma$. The secondary charged particles in Stage III of Fig. 1 arise from the slowing down of the primary charged particles producing electron-ion pairs and resulting in ionization, excitation and dissociation. Except for the first stage in Fig. 1, we can, in principle, intercept the energy flow at any subsequent stage to generate electricity.

The final heat stage, stage IV in Fig. 1, is distinguished from stages II and III by the fact that the maximum energy conversion efficiency of a heat cycle operating between a hot reservoir T_{hot} and a cold reservoir T_{cold} is the Carnot efficiency:

$$\eta_{Carnot} = \frac{T_{hot} - T_{cold}}{T_{hot}} \tag{1}$$

It is important to appreciate that if we wish to generate electricity without a heat cycle, we have to somehow intercept the energy flowing from the charged particles (stages II or III) into thermal motion of the background absorbing medium (stage IV). Energy conversion from stages II and III does not involve heat energy and is, therefore, not Carnot-limited. In principle, therefore, the maximum theoretical efficiencies of these stages can be significantly higher than Carnot. However, practical conditions and requirements may considerably reduce these high theoretical values.

3. POSSIBLE ALTERNATIVE METHODS FOR NEUTRON ENERGY CONVERSION

3.1 A Survey of the Methods

What alternative methods are open to us for producing electricity from one of the three energy-flow stages, II through IV, in Fig. 1? In Table 1, we list eight schemes which could, in principle, be utilized for electricity generation from fusion neutrons. We have denoted in the Table those schemes which are Carnot-limited, i.e., involve energy flow to the final heat stage (stage IV) in Fig. 1 before conversion to electricity. We have also denoted those methods we consider fusion-specific, i.e., those which exploit the unique properties of DT fusion. Method 1 in Table 1 is the conventional steam-cycle and is included for completeness. Methods 7 and 8 are novel neutron energy conversion schemes currently under investigation at Lawrence Livermore National Laboratory and will be discussed in greater detail below.

Table 1 is not intended to be an exhaustive list of possible methods for neutron energy conversion but serves to illustrate that boiling water in a conventional steam-cycle may not necessarily be the only complement to a DT fusion power core.

3.2 Non-Fusion-Specific Methods

Thermoelectric conversion[10] (i.e., the Seebeck effect, where two dissimilar materials at a hot junction develop an EMF) and thermionic conversion[11] (i.e., thermionic emission of an electron current from a hot cathode and collection by a cold anode of different work function), have seen considerable application in space power systems where they have been employed as electrical conversion schemes for either nuclear reactor or isotopic heat sources. Both schemes have the advantage of simplicity and, therefore, potential cost savings. However, in space applications, requirements for simplicity, compactness, high temperature operation, and reliability can be more important than high efficiency. In this regard, practical thermionic convertors typically achieve less than one-half Carnot efficiency, while the lower power density thermoelectric convertors achieve about one-sixth Carnot.

The principle of electrohydrodynamic (EHD) conversion[12] is to electrostatically retard the motion of a conducting thermally-vaporized working fluid thereby converting kinetic energy into electrostatic potential energy; the laboratory analog of this is the Van de Graaff generator. EHD conversion has seen only a low level R&D history and has not apparently demonstrated efficiencies sufficient to warrant further research at this time.

Accordingly, given the low practical efficiencies of methods 2 through 4 in Table 1, it is unlikely they will be an economic competitor to the steam cycle for fusion energy conversion. In addition, none of the first four conversion schemes are fusion-specific and could, in principle, be mated to any heat source: fossil, solar, fission or fusion. Therefore, if they were deemed attractive for fusion, they would probably be attractive for these other heat sources. Only the steam cycle with its extensive development through the years to a high degree of sophistication -- albeit an expensive and complex sophistication -- has proved economically viable for large scale electricity generation.

3.3 Fusion Specific Methods

Methods 5 through 8 in Table 1 are interesting in view of the fact that they are fusion specific, i.e., exploit one or more unique properties of DT fusion for their operation. In some instances, we could envisage their deployment in gas-cooled fission reactors, although they may be of limited applicability due to the disruption of the core criticality by conversion systems of any appreciable size. Note also that method 7 is Carnot-limited (i.e., makes use of the final heat stage [stage IV] of the neutron energy flow - see Fig. 1), whereas methods 5, 6 and 8 depend on energy conversion from the primary or secondary charged particle stages (stages II and III in Fig. 1).

In direct charged-particle conversion (method 5), the idea is to intercept the neutron energy flow at stage II in Fig. 1 and perform direct conversion of the kinetic energy of the primary neutron-induced charged particle to electric potential energy by high-voltage retarding fields. This is a high voltage, low current neutron analog of the electrostatic plasma direct convertors at the ends of a tandem mirror reactor (see, for example, ref. 7). The "blanket" region of the fusion reactor would be formed of alternate layers of emitting and collecting electrodes. Primary charged particles produced by neutron interaction in the thin emitter plates would ideally be collected at zero kinetic energy by the collector electrodes by virtue of their high retarding potential. The emission plate could, for example, be constructed either of fissionable material (e.g., ^{235}U) yielding high energy fission fragments, or hydrogenous material yielding knock-on protons from the (n,p) reaction. Such neutron-conversion systems have been tested experimentally in the neutron flux of fission reactors.[13] However, due to system problems with secondary electron emission and voltage breakdown, and inherent effects of energy and angular spreads of the emerging charged particles, this method held little hope for efficiencies higher than 5-10%. In addition, in the magnetic fusion reactor, direct conversion of neutron-induced electrons (via gamma production, see Fig. 1) is impracticable due to the high magnetic fields -- the small gyroradii of high energy electrons (< 1 mm) prevents them from crossing the gap to the collecting electrode. We should note, however, that this latter effect should effectively suppress secondary electron leakage currents in a fusion primary-charged-particle conversion scheme; leakage currents severely limited the performance of the fission reactor tests of this method. However, in the fusion reactor application, there is the additional problem of integrating a sufficient number of thin (i.e., - charged particle range) emitting surfaces, sufficiently separated from the collecting electrodes to avoid voltage breakdown, within the "blanket" region between the first wall and superconducting magnet. In this regard, inertial-confinement fusion reactors would make better use of this method, but there is still the problem of low efficiency.

In ionization-electric conversion (method 6), energy flow is intercepted at stage III of Fig. 1. Here, we rely on the separation of secondary ion-pairs produced by the slowing down of the neutron-induced primary charged particles. The separation could be effected by a voltage difference produced either by electrodes of different work functions or in some form of p-n semiconductor junction. This low voltage, high current conversion scheme is the analog of a radiation detector but with an internally generated EMF rather than one supplied from an external source. Again, however, low efficiency is a potential problem with this method.[14] The limiting efficiency is given by the ratio of the ionization potential

(I) of the absorbing medium to the average energy required to create an ion-pair (i.e., the W-value). We could minimize the fraction of the W-value going to excitation rather than ionization, by selecting absorbing media with high ionization potential (e.g., helium). However, while I/W determines the theoretical limiting efficiency, in practice losses of ion-pairs by recombination may limit the current and power density in the "unit cell". Miley[14] calculates, for example, that with high recombination, a cell power density of less than 1 $\mu W\ cm^{-3}$ would be obtained for an incident fission neutron flux of $10^{14}\ n\ cm^{-2}\ s^{-1}$. Radiation damage to a semiconductor version of this method is an additional problem for fusion applications. Further research into this method may indicate new avenues for higher efficiency.

Accordingly, notwithstanding the conventional steam cycle, only two of the novel methods in Table 1 appear to possess sufficient potential at this time to warrant further consideration as methods for DT neutron energy conversion to electricity, namely: in-situ radiation-catalyzed MHD conversion, and excimer-channeled UV conversion. These two methods are discussed further in the sections below. It is not intended in the following sections to give a detailed technical account of these two processes -- indeed, both are only at an early stage of development -- but rather to outline the general principles to emphasize that fusion neutron energy conversion could perhaps be effected by novel means and to stimulate further thinking in this area.

4. IN-SITU RADIATION-CATALYZED MHD CONVERSION

Previous work on traditional combustion-gas, open-cycle MHD (magnetohydrodynamic) and two-phase liquid-metal closed-cycle MHD, were limited to economically marginal topping cycles (see, for example, ref. 15). In this novel application to fusion, Logan[16] emphasizes the fact that the magnetic fusion reactor offers new ingredients to overcome the most serious obstacles to previous conventional MHD development: first, the existing fusion reactor magnets can be used in-situ to function as the usually expensive MHD magnets; second, x-ray bremsstrahlung and microwave synchrotron radiation from the plasma can be used to enhance the conversion efficiency of neutron heat within the integral MHD generator channels. A schematic of the concept is shown in Fig. 2. The "catalyzing" synchrotron and bremsstrahlung plasma radiation superheats the MHD generator vapor to temperatures higher than local wall temperatures, and enhances the vapor conductivity through non-equilibrium ionization. In this way, the electron temperature in the working fluid can be maintained significantly above that of the vapor. Rankine cycles using cesium-seeded metal vapors enable us to locate the power conversion loop entirely within the reactor. Only the waste heat rejection fluid is sent to an external system. Net cycle efficiencies of 30-45% are estimated, so steam-bottoming cycles could be eliminated. This enables a truely "in-situ" generating scheme to be envisaged avoiding much of the cost and complexity of the conventional balance of plant. Note also that because we have no primary loop or steam generators external to the reactor core in this method, we reduce considerably the potential problem of tritium-contaminated water in the external plant.

The MHD generators would be built into remotely maintainable modules extending radially between magnet coils of the reactor. We should stress that the concept employs a Rankine cycle with the working fluid circulating <u>within</u> the "blanket" region. Consequently, the majority of the blanket neutron energy supplies heat of vaporization for a relatively small liquid flow and reduces to low levels the pumping power required to return the liquid to the first wall. The plasma x-ray bremsstrahlung would be transmitted through low-z windows to enhance the ionization and, therefore, the conductivity of the high-z vapors while escaping synchrotron radiation would be piped through over-moded waveguides. Candidate vapors for the scheme include mercury (b.p. 630 K), cadmium (b.p. 1040 K), zinc (b.p. 1186 K), and magnesium (b.p. 1376 K). Low ionization-potential seeds as admixtures (< 1%) such as cesium or potassium would enhance the non-equilibrium ionization. Tritium breeding for DT reactor applications would be accomplished near the first wall and selected isotopes of the cadmium and/or mercury working fluids with low neutron capture cross sections are likely to be rquired. Finally, high temperature pebble bed vaporization zones will probably require the employment of refractory metals such as molybdenum and vanadium, and ceramics such as SiC.

While integrated blanket designs have not yet been completed for this new concept, the thermodynamic efficiency of binary cadmium-mercury Rankine cycles have been assessed as functions of temperature and pressure. These are shown in Fig. 3 along with a schematic of the configuration. Joule dissipation losses, heat loss to cooler walls, and friction losses at Mach 2 in the channels are included. Cadmium is vaporized in the high temperature pebble bed zones at the front of the blanket and directed through the primary MHD generator channels. Subsequent condensation of the cadmium vapor at 770°K is used to boil mercury to feed adjacent mercury MHD channels. Note that efficiency favors lower pressures at the channel condensers, whose cross-sectional areas will be constrained by available space between magnet coils. Vaporizing nozzle pressures are about 0.5 atm, conducive to low stress, high temperature, pebble-bed type blankets. The results of Fig. 3 suggest, for vapor-stagnation temperatures in the range of 1500° to 2000°K, typical blanket fields of 5T, heat fluxes of 2-5 MW_{th}/m^2, and 10% synchrotron heating fractions extractable from DT plasmas, that net cycle efficiencies competitive with steam cycles might be achieved with in-situ MHD, without any steam bottoming cycles. The relatively high heat rejection temperatures (150 to 220°C) could be exploited for valuable process heat. A comprehensive technical paper on this proposed conversion scheme will be issued in due course.

5. EXCIMER-CHANNELED UV CONVERSION

The method is due to an original idea by George[17] which requires the conversion of the secondary charged particle energy (stage III in Fig. 1) via excitation to narrow bandwidth, single-line UV radiation with high efficiency in an appropriate excimer medium. Subsequent high efficiency conversion of the UV photon energy to electrical energy is achieved by specially tailored UV photocells.

An "excimer" is formed by the attachment of the excited state of one closed shell atom (e.g., He) to a ground state atom of the same species to form a strong chemical bond. Such an attribute is usually restricted to the bound excited states of rare gas or group II elements. The common attribute of excimers is the property of "channeling" by which the energy flow from incident charged particles through the excimer bound-free transition to the narrow band UV photon output can occur with very high efficiency. Rare gas dimers, e.g., Xe_2^*, Kr_2^*, Ar_2^*, He_2^*, are particularly good examples of this. Measurements at Lawrence Livermore National Laboratory in connection with the excimer laser program have demonstrated high channeling probability where experiments for a variety of both excitation sources (e.g., electrons, fission fragments, protons) and particle densities have given efficiency values ranging from a few percent to as high as 100%.[18,19,20] It should be stressed that we are not requiring the fusion blanket to be a neutron-pumped laser, but simply a fluorescence medium to funnel neutron energy via secondary charged particle production (stage III in Fig. 1) into UV light with high efficiency.

Due to the nature of the UV output, i.e., monochromatic with narrow line width, it is possible to envisage specially tailored UV photocells with energy band gaps matched to the photon energy. Unlike the case of the conventional solar cell which must accommodate a broad complex emission spectrum with a resulting efficiency of only ~ 20-30%, the monochromatic nature of the UV emission implies that conversion efficiencies of ~ 80-90% might be achievable.[21] Overall conversion efficiencies from neutron energy to electricity might be expected to reach 40-60% by this method and further scoping studies are currently being conducted.

6. WHAT ARE THE ECONOMIC IMPLICATIONS OF NOVEL CONVERSION SCHEMES?

Both the excimer-channeled UV conversion scheme and the in-situ radiation-catalyzed MHD conversion scheme in the sections above are, at present, in a preliminary concept phase. There are many technical issues which must be addressed, both theoretically and experimentally, before any reasonable assessment of their final potential can be made. However, we can attempt a rough evaluation of the economic benefits of their integration into a fusion reactor core in place of a conventional steam cycle.

In Table 2, we show our approximate economic evaluation of replacing the conventional helium-cooled LiPb blanket system and associated steam-cycle in the 600 MWe MINIMARS tandem mirror reactor[7] with an in-situ radiation-catalyzed MHD scheme. Similarly, in Table 3 we take the original STARFIRE tokamak reactor[1] with conventional water-cooled $LiAlO_2$ blankets and steam-cycle balance of plant, and compare it to the innovative 1200 MWe Microwave Tokamak[22] with in-situ MHD power conversion. Note that in Table 2, we have assumed the same MINIMARS fusion power core for both the conventional steam-cycle and innovative MHD conversion systems. By contrast, in Table 3, the Microwave Tokamak has several novel features relative to the original STARFIRE reactor design over and above the MHD conversion scheme. Accordingly, we may see different economies in the comparison of "before and after" in Table 2 and Table 3. We should also note that the original direct costs in the first column of both tables came from different studies and, therefore, we might expect some degree of variation in the relative values.

In comparing the principal direct cost of accounts for MINIMARS for conventional and novel conversion schemes in Table 2, we note that with the exception of Land and Land Rights (account 20), there are appreciable economies in all other cost account areas. In Structures and Site Facilities (account 21), we obtain large savings due to the lack of requirements for buildings for primary loop and heat exchangers, for turbine plant, and for auxiliary structures associated with the conventional steam cycle. In the case of the Reactor Plant Equipment (account 22), the differences are only ~ 7%. Here, for the novel energy conversion plant, we make savings of ~ 60M$ due to having no primary loop and heat exchangers but are penalized somewhat by more complex and expensive blanket and magnet systems due to the in-situ MHD cycle. The Turbine Plant Equipment account (account 23) shows, of course, the biggest cost savings, since the only item we have to provide for in this category is the waste heat rejection system from the in-situ MHD generators. Interestingly, for novel conversion schemes which are not Carnot-limited (e.g., the excimer-channel UV scheme), our waste heat rejection could be performed with a large ΔT, thus minimizing the volume of the heat rejection system and employing compact mechanical draft cooling assemblies in place of large traditional cooling towers. In addition, we can make appreciable savings in the Electric and Miscellaneous Plant Equipment (accounts 24 and 25, respectively) due to the lack of requirements for systems associated with external conventional balance of plant. It might be argued that the cost savings for accounts 24 and 25 could be even larger than those indicated. Finally, in Table 2, we take advantage of the significant simplification of the novel energy conversion plant and allow both an availability increase from 75% to 80% (remember the bulk of unscheduled downtime in present day fission reactors is attributable to balance of plant problems) and a decrease in construction time from 4.6 to 4 years (we already take credit in the conventional version of MINIMARS for streamlined construction and licensing due to standardized factory-built modules and inherent/passive safety[7]).

In Table 3, we show a slightly more detailed breakdown of the major capital costs in order to emphasize additional features of the Microwave Tokamak. As with MINIMARS in Table 2, we allow large economies in Structures and Site Facilities (account 21) due to the lack of requirements of buildings for the balance of plant, but take additional savings for a novel silo reactor vault (see Ref. 22). In the Reactor Plant Equipment (account 22), we again benefit from having no primary loop and heat exchanger but must pay the penalty for the increased cost of the MHD generators over the conventional STARFIRE blanket. We should also note here that, in the case of a toroidal reactor, the accommodation of novel integral conversion schemes will in general lead to a somewhat larger and more complex fusion power core assembly because the integration of the power conversion modules in the critical region between the first wall and the magnets is not likely to result in as compact a configuration obtained with the conventional blanket. By contrast, the economics of the tandem mirror reactor, with its simple linear geometry central cell, is very insensitive to dimensional changes in this region. However, in the Microwave Tokamak, we have also implemented advanced high-current-density magnet designs.[22,23] The net result is a slight saving in the magnet costs over STARFIRE.

Other savings in the reactor plant equipment of Table 3 include advanced shield designs and lower heating powers due to synchrotron drive and bootstrap current;[22] these are not related to the MHD conversion system. As with MINIMARS in Table 2, we make appreciable savings in the Turbine, Electrical, and Miscellaneous Plant Equipment (accounts 23, 24 and 25). Similarly, with the same logic as above, we allow an availability increase from the STARFIRE value of 75% to 80% and a decrease in the plant construction time from the STARFIRE value of 6 years to 4.5 years to reflect the large degree of simplification in the external plant.

From Tables 2 and 3, the assumed economic benefits of our novel conversion schemes are evident in the decrease in the cost of electricity from 38.3 to 24.0 mills/kWhr for a Tandem Mirror at 600 MWe, and from 31.4 to 17.4 mills/kWhr for the 1200 MWe Tokamak, i.e., savings in the vicinity of ~ 40% and 45%, respectively! We again stress that the Microwave Tokamak has additional improvements relative to STARFIRE over and above the energy conversion system. Accordingly, for the energy conversion system alone, we would expect savings of the same order as those for the tandem mirror, i.e., ~ 35-40%. Economies of these magnitudes with novel fusion-specific neutron conversion schemes, would demonstrate a significant advantage for fusion over conventional forms of electricity generation. Note particularly in Tables 2 and 3 that the fraction of the total direct cost attributable to the (fusion) Reactor Plant Equipment (account 22) has increased from ~ 56% to ~ 72-75%, demonstrating the motivation in this paper to innovate the systems external to the fusion power core. Of course, innovations in the latter will improve (i.e., reduce) the cost of electricity still further.

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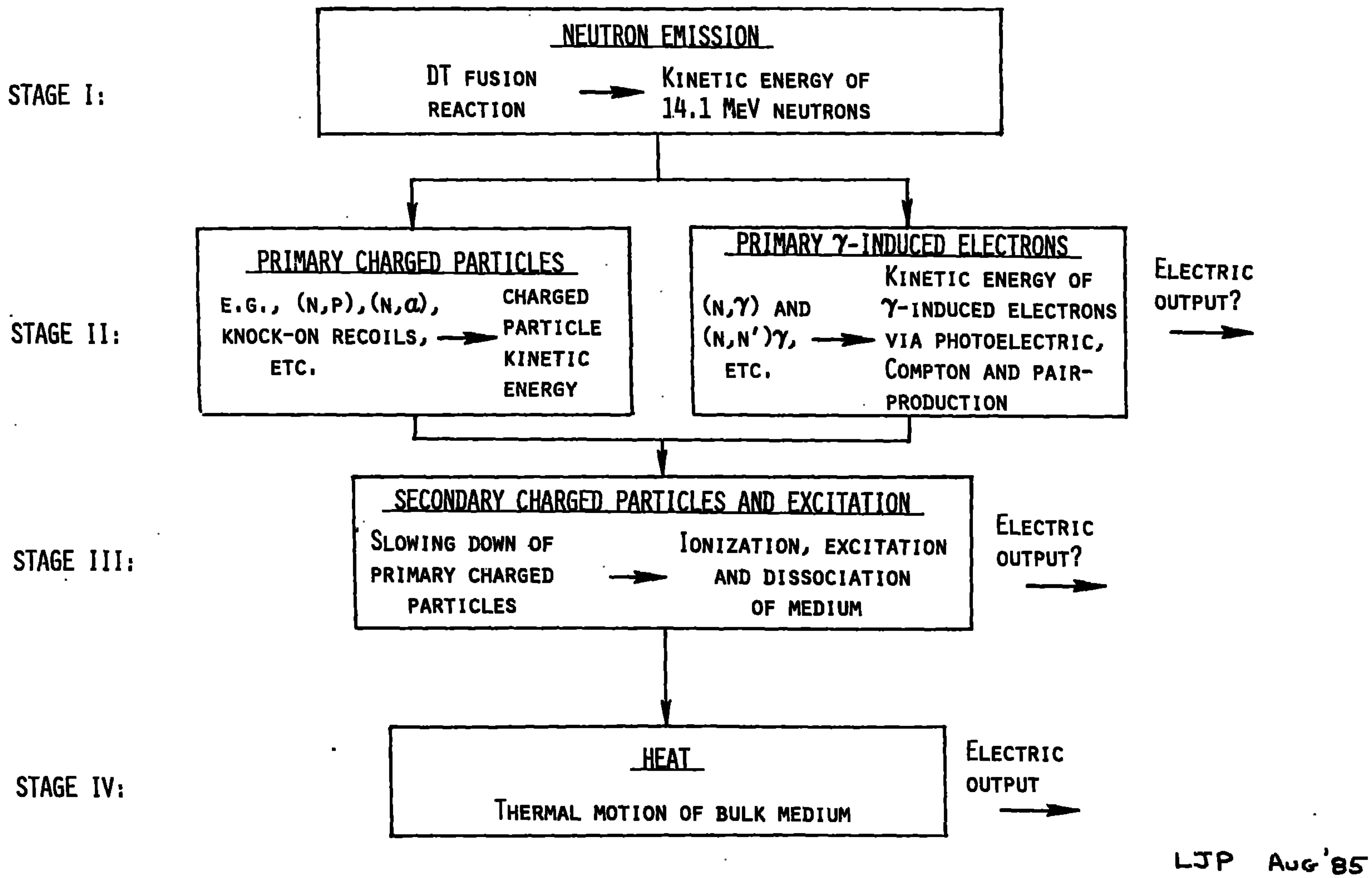

Fig. 1. The four stages of energy flow from DT neutrons to heat.

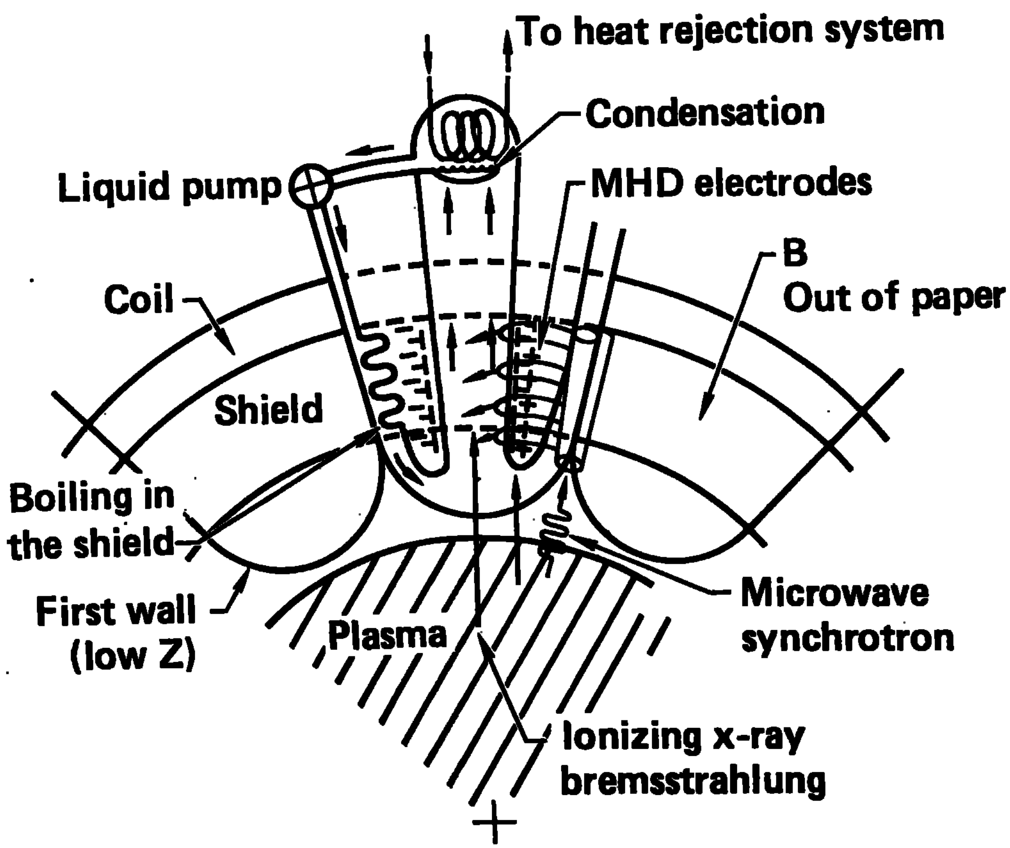

Fig. 2. Schematic of the in-situ radiation-catalyzed MHD conversion scheme.

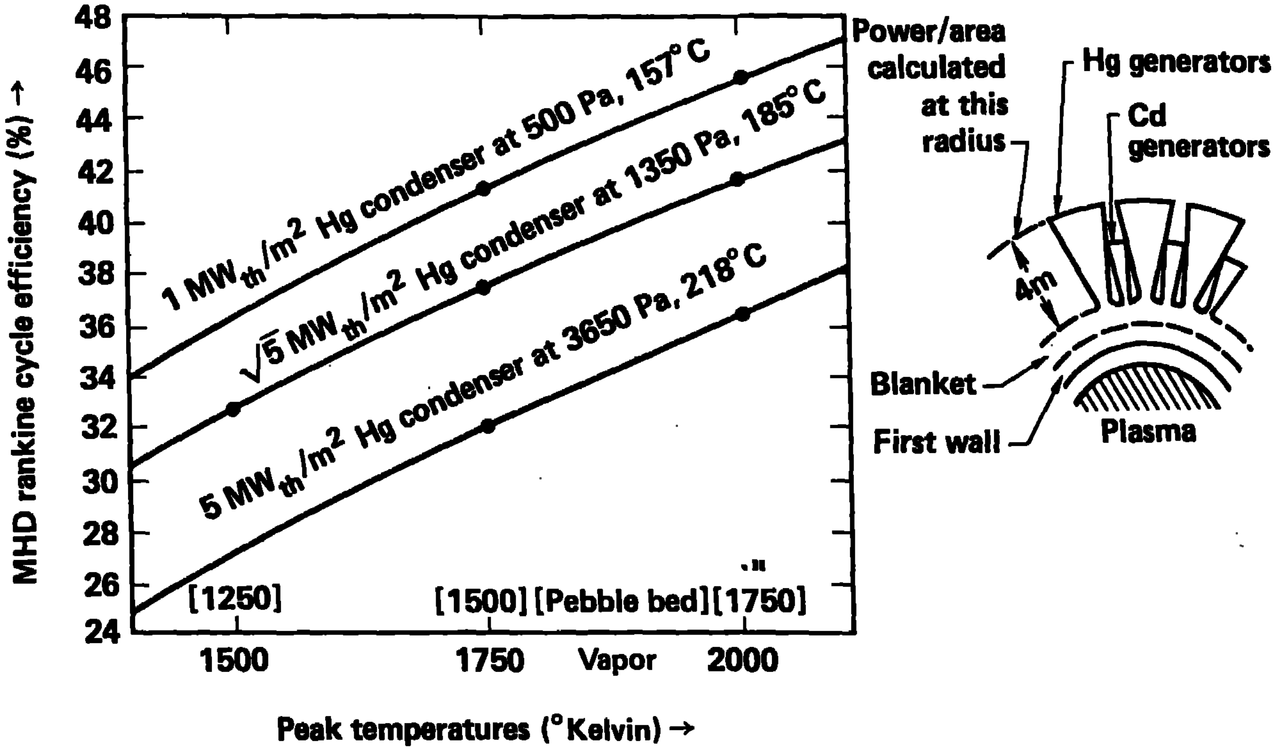

Fig. 3. Thermodynamic efficiency of a binary cadmium-mercury in-situ MHD cycle as a function of the peak stagnation temperature of the cadmium vapor; the mercury condenser power/unit area, pressure and temperature is shown as a parameter. The asociated temperature of the front pebble bed is indicated with the corresponding cadmium vapor temperature. The inset figure indicates the geometry of the calculation and the following conditions were assumed: B = 5T, fraction of fusion power emitted as synchrotron radiation = 0.1, ratio of surface area of cadmium generator channel to that of the mercury generator = 0.3. Note that efficiency favors low pressures at the mercury channel condensers.

TABLE 1.

Alternative Methods for Fusion Neutron Energy Conversion to Electricity

Method	Fusion-Specific?	Carnot-limited?
1. Conventional steam cycle	No	Yes
2. Thermoelectric conversion	No	Yes
3. Thermionic conversion	No	Yes
4. EHD (electrohydrodynamic) conversion	No	Yes
5. Ionization-electric conversion	Yes	No
6. Primary charged-particle direct conversion	Yes	No
7. In-situ radiation-catalyzed MHD conversion	Yes*	Yes
8. Excimer-channeled UV-electric conversion	Yes	No

*May have (limited) application to gas-cooled fission reactors.

TABLE 2.

The Economic Benefits of Novel Neutron Energy Conversion

for a Tandem Mirror Reactor at 600 MWe

	Conventional Blanket and Steam-Cycle BOP	Novel In-Situ MHD Conversion System
Direct Cost Accounts (M$):		
20 Land and Land Rights	5.0	5.0
21 Structures and Site Facilities	170	78.4
22 Reactor Plant Equipment	550.4	515.8
23 Turbine Plant Equipment	156.5	30.0
24 Electric Plant Equipment	64.4	41.8
25 Miscellaneous Plant Equipment	34.4	22.4
Total direct cost (M$)	981	693
Fraction of total direct cost in Reactor Plant Equipment	0.561	0.744
Availability	0.75	0.80
Construction time[a] (yr)	4.6	4.0
Cost of electricity[b] (mills/kWhr)	38.8	24.0

[a]Period over which interest and escalation is incurred on plant capital cost. The total construction lead time would be about one year longer than this.

[b]Computed by recommended methodology of Ref. 24 (levelized costing, zero inflation and escalation).

TABLE 3. The Economics of Novel Neutron Energy Conversion for a Tokamak Reactor at 1200 MWe.

	STARFIRE with Conventional Steam-Cycle BOP		The Microwave Tokamak with Novel In-Situ MHD Conversion System[a]	
Direct Cost Accounts[b] (M$):				
20 Land and Land Rights	3.3		3.3	
21 Structures & Site Facilities	346.6		121.3	
22 Reactor Plant Equipment:	968.7		748.8	
Blankets & primary loop		175.0		156.5
Shielding		214.0		107.0
Magnets		197.3		167.7
Primary structure & support		60.7		60.7
Heating & power supplies		99.4		49.7
Other[c]		222.3		207.2
23 Turbine Plant Equipment	249.7		64.7	
24 Electric Plant Equipment	117.3		76.2	
25 Miscellaneous Plant Equipment	40.8		26.5	
Total Direct Costs (M$)	1726		1041	
Fraction of total direct cost in Reactor Plant Equipment	0.561		0.719	
Availability	0.75		0.8	
Construction time (yr)	6		5	
Cost of Electricity[d] (mills/kWhr)	31.4		17.4	

[a]The Microwave Tokamak[22] contains other improvements in addition to the MHD conversion scheme.

[b]1980$.

[c]Includes cryoplant, fueling, maintenance equipment, I&C and spare part allowance.

[d]Computed via recommended methodology of Ref. 24 (levelized costing, zero inflation and escalation).